Chinese Journal of Aeronautics, (2014),27(2): 420–424

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics
cja@buaa.edu.cn
www.sciencedirect.com

A novel in-plane mode rotary ultrasonic motor

Lu Xiaolong, Hu Junhui *, Yang Lin, Zhao Chunsheng

State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics & Astronautics, Nanjing 210016, China

Received 7 March 2013; revised 21 April 2013; accepted 9 May 2013
Available online 1 August 2013

KEYWORDS

In-plane vibration;
Langevin transducers;
No-bearing;
Rotary driving;
Ultrasonic devices

Abstract Ultrasonic motors have the merits of high ratio of torque to volume, high positioning precision, intrinsic holding torque, etc., compared to the conventional electromagnetic motors. There have been several potential applications for this type of motor in aerospace exploration, but bearings and bonding mechanism of the piezoelectric ring in the motors limit the performance of them in the space operation conditions. It is known that the Langevin type transducer has excellent energy efficiency and reliability. Hence using the Langevin type transducer in ultrasonic motors may improve the reliability of piezoelectric motors for space applications. In this study, a novel in-plane mode rotary ultrasonic motor is designed, fabricated, and characterized. The proposed motor operates in in-plane vibration mode which is excited by four Langevin-type bending vibrators separately placed around a ring-shaped stator. Two tapered rotors are assembled to the inner ring of the stator and clamped together by a screw nut. In order to make the motor more stable and convenient to fix, a thin cylindrical support is placed under the stator ring. Due to its no-bearing structure and Langevin transducer excitation, the prototype ultrasonic motor may operate well in aeronautic and astronautic environments.

1. Introduction

Requirements for actuators used in aircrafts or robotic arms for space exploration are much more rigorous than for those used in ordinary applications.[1–3] An ultrasonic motor, which is an actuator utilizing ultrasonic vibration to drive, has features such as electromagnetic interference free, low noise, light weight, compact structure, etc.[4,5] Thus, the ultrasonic motor is competitive compared to traditional electromagnetic motors while being applied as a mechanical driving unit in aeronautic and astronautic systems.

In previous research on morphing aircrafts in our lab, Liu et al.[6] designed a variable camber wing driven by ultrasonic motors (see. Fig. 1). It mainly consists of a driving governor, ultrasonic motors, inner support, and trailing edges. Multiple ultrasonic motors are employed to drive the trailing edges for realizing the wing morphing. The proposed mechanism was experimentally confirmed by the classical traveling wave rotary ultrasonic motors. For improving the stability of such a system, using ultrasonic motors with reliable and compact structures should be helpful.

Till now, ultrasonic motors are mainly divided into ultrasonic motors with bonding piezoelectric plates[7] and with Langevin transducers.[8,9] Ultrasonic motors with Langevin

* Corresponding author. Tel.: +86 25 84891681.
E-mail address: ejhhu@nuaa.edu.cn (J. Hu).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

1000-9361
http://dx.doi.org/10.1016/j.cja.2013.07.002

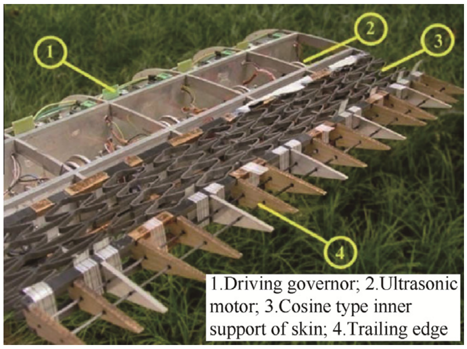

Fig. 1 Inner structure of the variable camber wing.[6]

transducers have good stability and high adaptability because no bonding material is used between piezoelectric and metal parts.[10,11] Jin and Zhao proposed a novel rotary ultrasonic motor using a bar-shaped transducer which has a simple structure; but the normal distribution of the Langevin transducer is not favorable for minimizing, and the clamping structure is not very stable.[12] Iula et al. proposed a high-power traveling wave ultrasonic motor which used a longitude Langevin transducer; but the size of the motor is too big.[13–15] In addition, Liu et al. did a lot of work in designing ultrasonic motors with Langvin transducers, and proposed a cylindrical traveling wave ultrasonic motor which had a compact structure.[16–18]

In this paper, a novel in-plane mode rotary ultrasonic motor is designed, analyzed, fabricated, and measured. Four bending Langevin transducers are distributed around the stator ring for exciting its in-plane flexural vibration. The appearance size is minimized by using the bending vibration mode of the Langevin transducers. A thin cylindrical support is placed under the stator ring which makes the motor's fixing more stable and convenient. Based on the simulation with ANSYS software, the size parameters of the stator and the basic working mode are determined. The merits of this prototype motor are as follows: compact structure, stable fixing, simple piezoelectric structure, same vibration mode, and good stability. Designing and measuring results give useful guidelines for using the ultrasonic motor in aerospace environments.

2. Structure design

2.1. Configuration of the motor

Fig. 2 shows the configuration of the novel in-plane mode rotary ultrasonic motor, which is mainly composed of the stator, rotor A, rotor B, a nut, and a leaf spring. Rotor A has a tapered bottom with a long shaft in the center. Being similar to rotor A, rotor B is also tapered but with a center hole holding the shaft of rotor A. Rotor A is pressed on the bottom driving face of the stator with the shaft through it. Rotor B is assembled with the shaft of rotor A and placed on the top surface of the stator. The leaf-shaped spring is assembled on rotor B and pressed by the nut which is screwed to the end of rotor A's shaft. Thus, two tapered rotors are fitted on the two conical driving faces of the stator, and the preload between the rotor and the stator can be adjusted by deformation of the leaf spring.

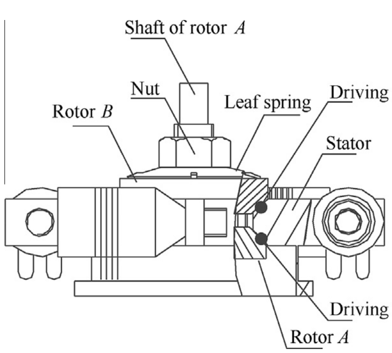

Fig. 2 Configuration of the ultrasonic motor.

Piezoelectric material in the transducers is PZT-8H. It has piezoelectric constant d_{33} of 200×10^{-12} C/N, electromechanical coupling factor k_{33} of 0.60, mechanical quality factor Q_m of 800, dielectric dissipation factor $\tan\delta$ of 0.5%, density of 7450 kg/m^3, and Curie temperature T_c of 300 °C.[5] Phosphor bronze is chosen for making the stator ring and the transducers' metal parts, and aluminum for making the rotor. Additionally, PTFE composite material is utilized as the friction layer adhered to the tapered faces of the rotors, which can make the performance of the motor more stable and keep the motor noise-free.

2.2. Construction of the stator

As shown in Fig. 3, the stator consists of one stator ring and four bending Langevin transducers (A_2, B_2, A_3, B_3). The stator ring can be divided into a top ring, a thin support, and a bottom base. There are two conical driving faces in the inner side of the top ring and many teeth are cut out for enlarging the vibration amplitude. Four Langevin transducers are assembled on the same side of corresponding projections with the length direction tangential to the top ring. The cylindrical support connects the top ring and the bottom base. The bottom base used for fixing the motor to a target surface has a thick ring-shaped structure which makes the motor's fixing more stable

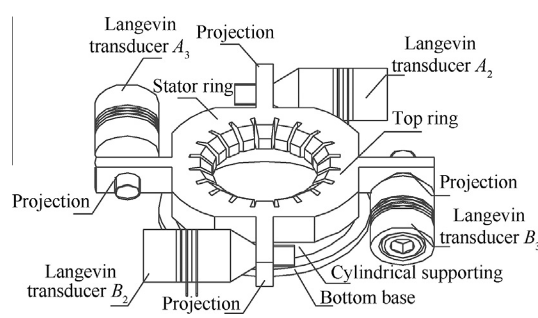

Fig. 3 Construction of the stator.

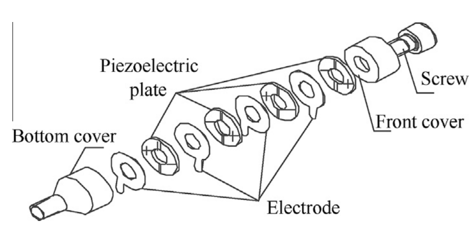

Fig. 4 Details of the Langevin transducer.

and convenient. The cylindrical support is for weakening the influence of fixed boundary on the vibration of the top ring.

Fig. 4 shows details about the bending Langevin transducer. It can be seen that the bending Langevin transducer mainly consists of one bottom cover, four electrodes, four piezoelectric plates, one front cover, and one screw. There are two conversely polarized areas in each piezoelectric plate and two adjacent plates have the converse polarity arrangement. Four piezoelectric plates are placed as shown in Fig. 4 and clamped together by the screw through the front cover to the bottom cover.

The piezoelectric plates in transducer A_2 have opposite polarization directions to their counterparts in transducer B_2, and so are those in transducers A_3 and B_3; the angular separation between transducers A_2 and A_3 is 90°, and so is that between transducers B_2 and B_3. Thus, when applied with the same driving voltage, transducers A_2 and B_2 have opposite bending directions, and so are the transducers A_3 and B_3. This arrangement can make the in-plane flexural operation mode of the top ring effectively excited.

3. Working principle

The novel ultrasonic motor employs the 5th flexural in-plane vibration mode in the top ring, which has five vibration wavelengths around its circumference, and its vibration direction is in the plane parallel to its top or bottom surface. As shown in Fig. 5, INPUT1 and GND denote the input sinusoidal AC voltage signal and the ground electrode, respectively. Transducers A_2 and B_2 vibrate in 2nd bending modes with 180° phase difference and a driving frequency close to the natural frequency of the 5th flexural mode of the stator ring, and a standing wave of the 5th flexural in-plane mode in the stator ring can be excited by the transducers. With the same driving frequency, another standing wave of the 5th flexural mode is excited in the stator ring when the input cosine AC voltage is applied to transducers A_3 and B_3. Meanwhile, it has a spatial phase difference of 1/4 wavelengths compared to the one excited by transducers A_2 and B_2. When the two groups of transducers are applied with AC voltages out of phase by 90° in time, these two standing waves in the stator ring can form a flexural travelling vibration wave in the xy plane of the stator ring. Therefore, the two rotors can be driven by the friction force at the interface between the stator and the rotor.

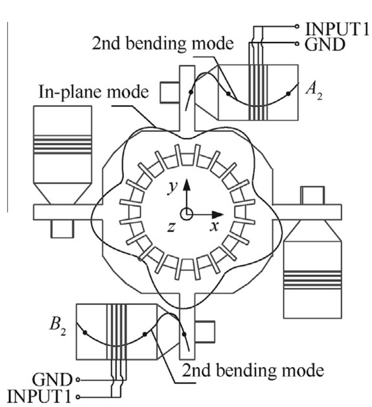

Fig. 5 Working principle of the stator.

4. Calculation

In order to determine the working vibration mode and modal frequency, ANSYS software is utilized for calculation. For saving the calculating time, only main structures of the stator are kept and others are simplified. Size parameters for calculation are as follows: the piezoelectric plate's size is 15 mm (outer diameter) × 6 mm (inner diameter) ×1 mm (thickness); the Langevin transducer's diameter is 15 mm and length is 27.6 mm; the top ring's outer diameter is 50 mm, inner diameter is 25 mm, and height is 10 mm; the number of teeth of the stator is 20. The calculated result of the working mode is shown in Fig. 6. It is observed that there are 5 wavelengths at the inner side of the stator ring and transducers A_2 and B_2 vibrate in 2nd bending mode, which demonstrate the working principle of the stator. The resonance frequency of this working mode is 50.6 kHz. With the sinusoidal driving voltage 100 V (zero to peak) at resonance frequency applied to transducers A_2 and B_2, the harmonic analysis is executed while the damping ratio is assumed to be 0.3%. The calculated radial vibration amplitude of the 5th in-plane mode is about 2.0 microns.

5. Experiments

According to the structure and size parameters of the motor proposed above, a prototype motor is fabricated (see Fig. 7).

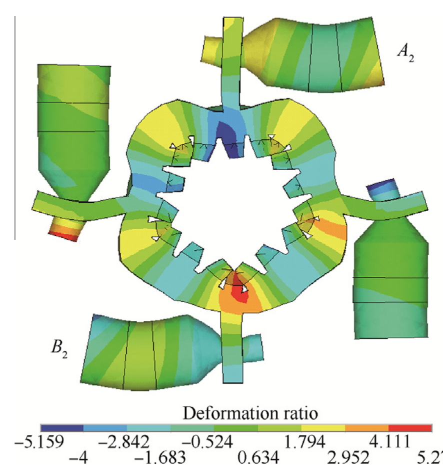

Fig. 6 Vibration mode of the stator.

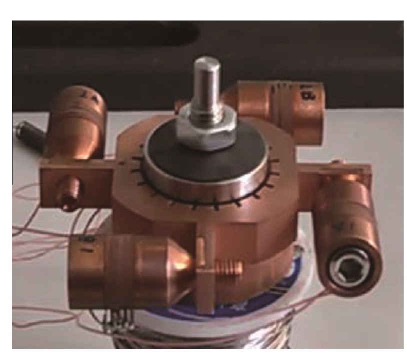

Fig. 7 Image of the prototype motor.

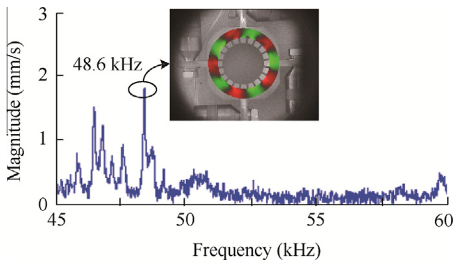

Fig. 8 Vibration measurement of the stator.

A Laser Doppler vibrometer system (PSV-300F-B) is used to measure the vibration characteristics of the stator. Considering that the stator ring's in-plane vibration mode cannot be measured directly, the stator's top surface is chosen as the measured area accordingly. Due to the Poisson effect, the stator's top surface has out-of-plane vibration as the stator is excited to vibrate. Fig. 8 shows the measured average vibration magnitude versus operating frequency when transducers A_2 and B_2 are driven by a 100 V (zero to peak) voltage. It can be seen that the resonance frequency is 48.6 kHz which is somewhat smaller than the calculated value. This may be caused by the deviation in the fabrication and assembling processes. At the resonance point, the measured vibration mode basically confirms the motor's working principle and FEM result. In the following experiments, if not mentioned, 48.6 kHz is chosen as the operating frequency and the pre-load between the stator and the rotor are tuned to be 100 N.

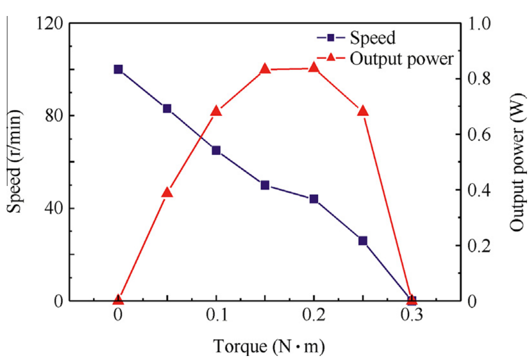

Fig. 9 Mechanical characteristics of the prototype motor.

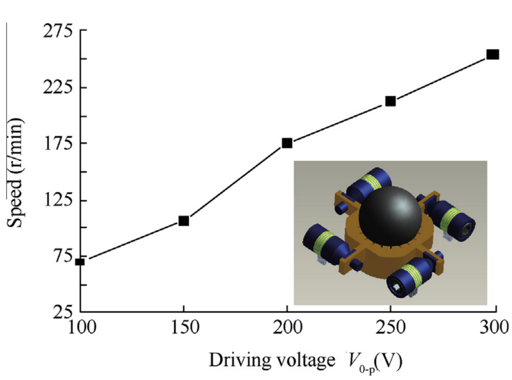

Fig. 10 Rotating speed versus input voltage for a ball-shaped metal rotor.

The mechanical characteristics of the prototype motor are measured. Transducers A_2 and B_2 work at resonance with sinusoidal driving voltage 200 V (zero to peak) and transducers A_3 and B_3 work at resonance with cosine driving voltage 200 V (zero to peak). The measured results are shown in Fig. 9. It can be seen that the stalling torque is 0.3 N·m, the no-load speed is 100 r/min, and the maximum output power is around 0.82 W with an output torque of 0.2 N·m. The measured results show that this prototype motor has a good performance at the driving frequency of around 48.6 kHz.

This prototype motor's stator can also be used to directly drive a ball-shaped rotor. Fig. 10 shows the measured result of rotating speed versus input voltages for a ball-shaped metal rotor with a mass of 190 g and a diameter of 36 mm. It can be seen that as the driving voltage increases, the rotating speed of the prototype motor increases and the relationship is almost linear. It is about 255 r/min at driving voltage 300 V (zero to peak). Experiments show that this prototype motor can operate stably in the driving voltages.

6. Conclusions

(1) A novel in-plane mode rotary ultrasonic motor is proposed and investigated in this work. This ultrasonic motor has a compact structure and is convenient for fixing. The motor has no bearing and is excited by Langevin transducers, which means its structure is reliable and thus fits for aeronautic and astronautic applications.
(2) Based on the FEM simulation, the dimensions of the prototype stator are determined. A prototype motor is fabricated, and the measured vibration characteristic of the stator confirms the proposed working principle and FEM results.
(3) The mechanical characteristics show that the prototype motor has a good performance. The no-load speed is about 100 r/min and the stalling torque is 0.3 N·m. For a ball-shaped metal rotor, the maximum rotating speed is 255 r/min at 300 V (zero to peak) input voltage.

Acknowledgements

This project was supported by the National Natural Science Foundation of China (Nos. 51205203, 51275228, 51075212, and 91123020), Nanjing University of Aeronautics and Astronautics (Nos. 56YAH12015, 56XZA12044, and S0896-013), Innovation and Entrepreneurship Program of Jiangsu, the 111 Project (No. B12021), and PAPD.

References

1. Sherrit S. Smart material/actuator needs in extreme environments in space. In: *Proceedings of the SPIE smart structure conference* 2005; 2005. p. 335–46.
2. Maillarda T, Claeyssen F, LeLetty R, Sosniki O, Pages A, Carazo AV. Piezomechatronic based systems in aircraft, space and defense applications. In: *Proceedings of SPIE-the international society for optical engineering*; 2009 Apr 13; Orlando, USA; 2009. p. 7731.
3. Six MF. Rotating step by step piezomotor for nanopositioning and space. In: *Proceeding of 10th conference on new actuators*; 2006 Jun 14–16; Bremen, Germany; 2006. p. 353–6.

4. Ueha S, Tomikawa Y, Kurosawa M, Nakamura N. *Ultrasonic motors theory and applications*. Oxford: Clarendon Press; 1993.
5. Zhao CS. *Ultrasonic motors technologies and applications*. Beijing: Science Press; 2010.
6. Liu WD, Zhu H, Zhou SQ, Bai YL, Wang Y, Zhao CS. In-plane corrugated cosine honeycomb for 1D morphing skin and its application on variable camber wing. *Chin J Aeronaut* 2013;**26**(4):1–8.
7. Sashida T. Motor device utilizing ultrasonic oscillation, United States patent US 4562374; 1985.
8. Xian XJ, Lin SY. Study on the compound multi-frequency ultrasonic transducer in flexural vibration. *Ultrasonics* 2008;**48**:202–8.
9. Hu JH, Nakamura K, Ueha S. A noncontact ultrasonic motor with the rotor levitated by axial acoustic viscous force. *Electron Commun Jpn Part III Fundam Electron Sci* 1999;**82**(4):56–63.
10. Lu XL, Hu JH, Yang L, Zhao CS. A novel dual stator-ring rotary ultrasonic motor. *Sens Actuators A Phys* 2013;**189**:504–11.
11. Lu XL, Hu JH, Zhao CS. Analyses of the temperature field of traveling wave rotary ultrasonic motor. *IEEE Trans Ultrason Ferroelectr Freq Control* 2011;**58**(12):2708–19.
12. Jin JM, Zhao CS. A novel traveling wave ultrasonic motor using a bar shaped transducer. *J Wuhan Univ Technol Mater Sci Ed* 2008;**23**(6):961–3.
13. Iula A, Pappalardo M. A high-power traveling wave ultrasonic motor. *IEEE Trans Ultrason Ferroelectr Freq Control* 2006;**53**(7):1344–51.
14. Iula A, Corbo A, Pappalardo M. FE analysis and experimental evaluation of the performance of a travelling wave rotary motor driven by high power ultrasonic transducers. *Sens Actuators A Phys* 2010;**160**(1):94–100.
15. Iula A, Bollino G. A travelling wave rotary motor driven by three pairs of langevin transducers. *IEEE Trans Ultrason Ferroelectr Freq Control* 2012;**59**(1):121–7.
16. Liu YX, Chen WS, Liu JK, Shi SJ. A cylindrical standing wave ultrasonic motor using bending vibration transducer. *Ultrasonics* 2011;**51**(5):527–31.
17. Liu YX, Chen WS, Liu JK, Shi SJ. A cylindrical traveling wave ultrasonic motor using longitudinal and bending composite transducer. *Sens Actuators A Phys* 2010;**161**(1–2):158–63.
18. Liu YX, Liu JK, Chen WS. A cylindrical traveling wave ultrasonic motor using a circumferential composite transducer. *IEEE Trans Ultrason Ferroelectr Freq Control* 2011;**58**(11):2397–404.

Lu Xiaolong born in 1984, is currently a Ph.D. candidate at State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, China. He received his ME degree from Southeast University, China, in 2009. His research interests include design and experiments of ultrasonic motors driven in extreme environments.

Hu Junhui is currently a professor at Nanjing University of Aeronautics and Astronautics. He received his Ph.D. degree from Tokyo Institute of Technology, Tokyo, Japan, in 1997, and BE and ME degrees in electrical engineering from Zhejiang University, Hangzhou, China, in 1986 and 1989, respectively. He is a Chang-Jiang Distinguished Professor of the Ministry of Education of China, director of Precision Driving Lab at Nanjing University of Aeronautics and Astronautics (NUAA), and deputy director of State Key Laboratory of Mechanics and Control of Mechanical Structures, China.